PROGRESS AND STATUS OF THE S-DALINAC *)

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I. Introduction

In 1991, at the 5th Workshop on RF-Superconductivity, the first operation of the S-DALINAC, using its two recirculating beam transport systems and accelerating the beam three times in the main linac, was reported [1]. Since then the accelerator has produced beam for a wide variety of experiments demanding beams of quite different energies and currents. Therefore Sect. II gives a brief description of the experimental facilities at the S-DALINAC. It also summarizes to some extent the operation of the accelerator during the last two years and the present status of the superconducting cavities.

The following sections cover some of the technical developments which were finished since the last workshop. The Accelerator Control System, allowing full operation of the S-DALINAC from the remote control room, is described in Sect. III. It has been in operation for almost two years and has proven its reliability during this period of time. The development of RF couplers has reached a stage where a prototype of a new input coupler and several probe couplers have been operated in the accelerator for almost twelve months now. Section IV shows their design and performance. The modification of the room temperature 250 keV injection, necessary to achieve peak currents of some 2.5 A (as required for driving the FEL [2] at the S-DALINAC), is described in Sect. V, while Sect. VI gives an outlook on improvements and developments planned for the near future.

II. Operational Experience and Status

A layout of the S-DALINAC and its experimental facilities is displayed in Fig. 1. The left part shows the accelerator hall with the electron gun, room temperature injection, superconducting injector linac (top), main linac (center), and the two recirculating beam-

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*) Supported by the Bundesministerium für Forschung und Technologie (BMFT) under contract numbers 06 DA 641 I and 05 345 EA I.

lines (bottom). Experiments are set up in several locations: The beam from the injector is used for the investigation of channeling radiation and nuclear resonance fluorescence (1) at energies below 10 MeV. The FEL is located along the main linac (2a) and its infrared radiation is guided through an evacuated optical transfer line to the optics lab (2b), some 50 m away from the optical cavity of the FEL. After extraction into the experimental hall the beam from the S-DALINAC has been used extensively during the last two years for the investigation of channeling radiation (3) produced at electron energies between 30 and 75 MeV and for electron scattering experiments at the new QCLAM spectrometer (4) whose large solid angle and momentum acceptance allow for coincidence experiments of the type (e,e′x) as well as for single arm (e,e′) measurements. The addition of a magnetic bypass system (5) during the first months of this year now allows for 180° scattering experiments with the QCLAM spectrometer. For high resolution single arm scattering experiments the energy loss spectrometer arrangement (6) is still available.

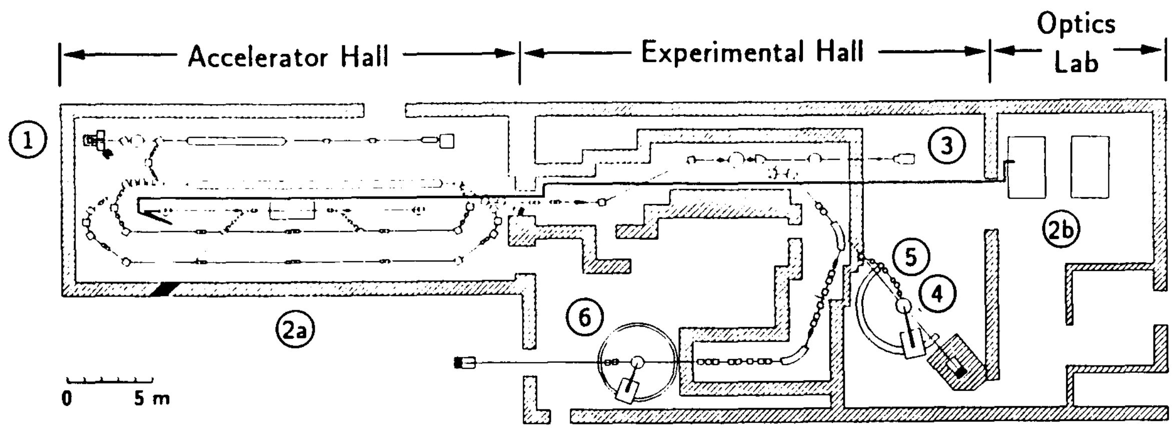

Fig. 1 *Layout of the S-DALINAC and its experimental facilities: (1) low energy channeling, (2a) FEL with (2b) optics lab, (3) high energy channeling, (4) QCLAM spectrometer, (5) bypass for 180° scattering, (6) energy loss spectrometer.*

A brief summary of beam characteristics as being used for the different types of experiments is given in Tab. 1 below.

Table 1: Beam characteristics for different types of experiments.

Experiment	Energy (MeV)	Current (μA)	Mode
Nuclear Resonance Fluorescence	2.5 - 10	40	3 GHz, cw
Low Energy Channeling	3 - 10	0.01 - 10	3 GHz, cw
High Energy Channeling	30 - 75	1	3 GHz, cw
Electron Scattering	22 - 80	5	3 GHz, cw
Free Electron Laser	32 - 38	2700 (peak)	10 MHz, pulsed

It shows the wide dynamic range of the accelerator delivering beams at energies between 2.5 and 80 MeV with currents from as low as a few nA up to 40 μA. Generation of the beam used for driving the FEL with very high peak currents is described in Sect. V. Since its installation the accelerator has provided more than 7000 hours of beamtime, presently some 2000 hours per year are achieved in two or three periods of operation with a duration of several months each.

The present installation contains superconducting cavities made from niobium of different purity (RRR = 100 and RRR = 280). The average accelerating field measured with electron beam amounts to 6 MV/m. The 5-cell capture section, made from RRR = 30 niobium, was high temperature titanium treated [3] at the University at Wuppertal and is operated at a gradient of 7 MV/m. For the 20-cell cavities, gradients ranging from 4.4 to 10.1 MV/m are obtained. To avoid the severe degradation in Q_o after an intermediate warm-up and slow cool-down, which was observed for our prototype RRR = 280 cavity as well as for different cavities in other laboratories, all high-RRR cavities were fired at 750 °C for several hours in the UHV furnace at Wuppertal prior to their installation in the accelerator cryostat. Nevertheless, all cavities show a Q_o well below the design value of $3 \cdot 10^9$, presently they average some $1 \cdot 10^9$. In addition, a slight degradation in Q_o after several warm-up periods cannot be excluded. As a consequence, due to the very limited power of our helium refrigerator (100 W at 2 K), it is not possible to operate all of the cavities simultaneously at the highest gradient, instead it is necessary to use an optimized combination of gradients giving the highest possible energy gain for the given refrigeration power. Therefore the energy of the accelerator in cw operation is presently limited to some 80 MeV, whereas at a reduced duty factor of 50 % an energy of 104 MeV was obtained. A possible improvement of the situation is discussed in Sect. VI.

III. Accelerator Control System

While commissioning the accelerator, control of all beam transport devices and beam diagnostics as well as of the rf system and the electron gun was carried out by a local computer system. Since then a comprehensive and much more reliable system has been developed which now allows for a quite comfortable remote control of the S-DALINAC. Figure 2 shows the functional diagram.

The controller for more than 150 power supplies for dipole and quadrupole magnets and for steering coils, two multichannel ADCs, a control unit for eight Faraday cups, and the selection of view screens and their corresponding TV cameras used for beam diagnostics is handled by a DEC LSI 11/73. Hardware adapted programs interface between the different devices and a common data block which is used as the central parameter data base. All utilities necessary for machine control, like operator input, status information, parameter display, set up, and save/restore facilities, interface uniquely to one process control program. This is realized either by local software or by using DECnet / Ethernet from the remote control room. There, two workstations build a graphical user interface and direct access to the laboratories local area network is possible. For program development and long time storage of machine settings the remote control is part of the laboratory computer cluster. Three groups of four knobs each can be assigned to any beam transport device or RF control channel.

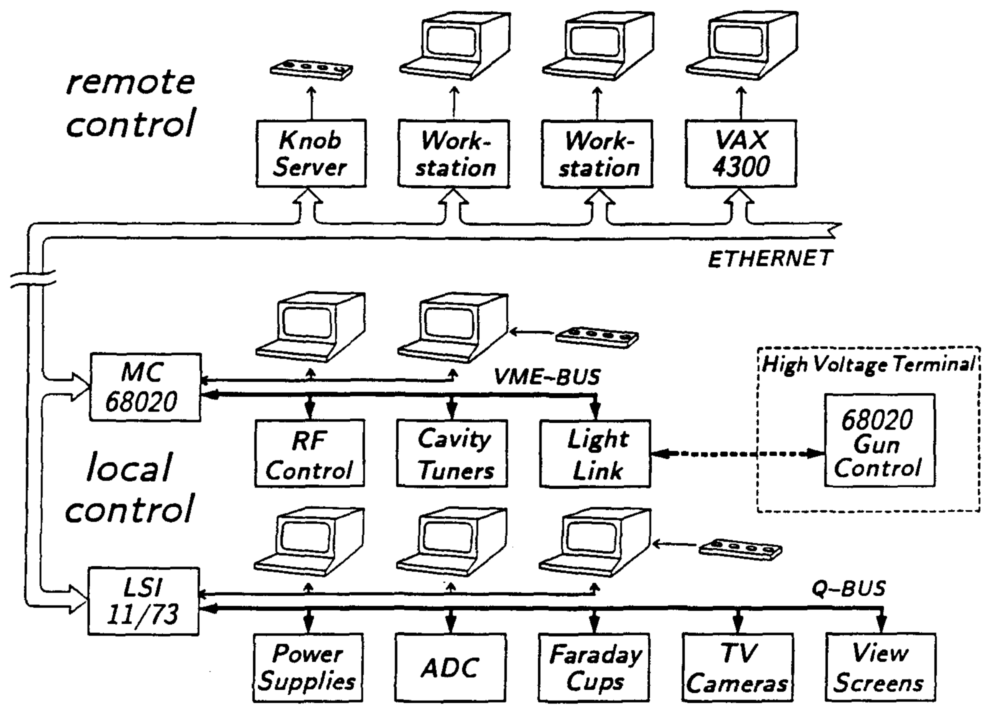

Fig. 2 *Accelerator Control System*

The RF control system consists of a 68020 microprocessor board which is directly connected to the RF control channels of the accelerating cavities and the drivers for their frequency tuners via VME - bus. The same microprocessor board acts as an interface to the electron gun input / output control board in the high voltage terminal, the connection being realized by fiber optics. Here again, either local control software allows for operating the RF system and the electron gun, or remote control is possible using a more comfortable user interface, where another group of four knobs assignable to all relevant parameters of the RF control circuits is used.

IV. RF Coupler Development

At present, ten of the eleven superconducting cavities of the S - DALINAC are still equipped with RF couplers as described in [4]. Several years of operational experience however called for a new development of the couplers eliminating some of the shortcomings of the original version. Figure 3 shows the new design of the input coupler together with its 7/8" coaxial RF input line. Two ceramic windows at room temperature allow the interior of the line to be part of the beam tube vacuum. The volume between the two windows is part of the cryostat insulating vacuum. Inner and outer conductor of the coaxial line are cryogenically connected to the liquid nitrogen cooled radiation shield of the cryostat via a $\lambda/4$ stub. The vertical position of the center conductor with respect to the outer conductor is kept fixed by a special connection just below the $\lambda/4$ stub. The bellows which is integrated into the lower part of the input line allows for a length variation of the outer conductor of as much as 20 mm. This results in a corresponding variation of the distance between the end of the center conductor (kept centered by a sliding teflon disc) and the intermediate coaxial resonator which performs the coupling between the input line and the superconducting cavity (indicated in the lower left part of Fig. 3).

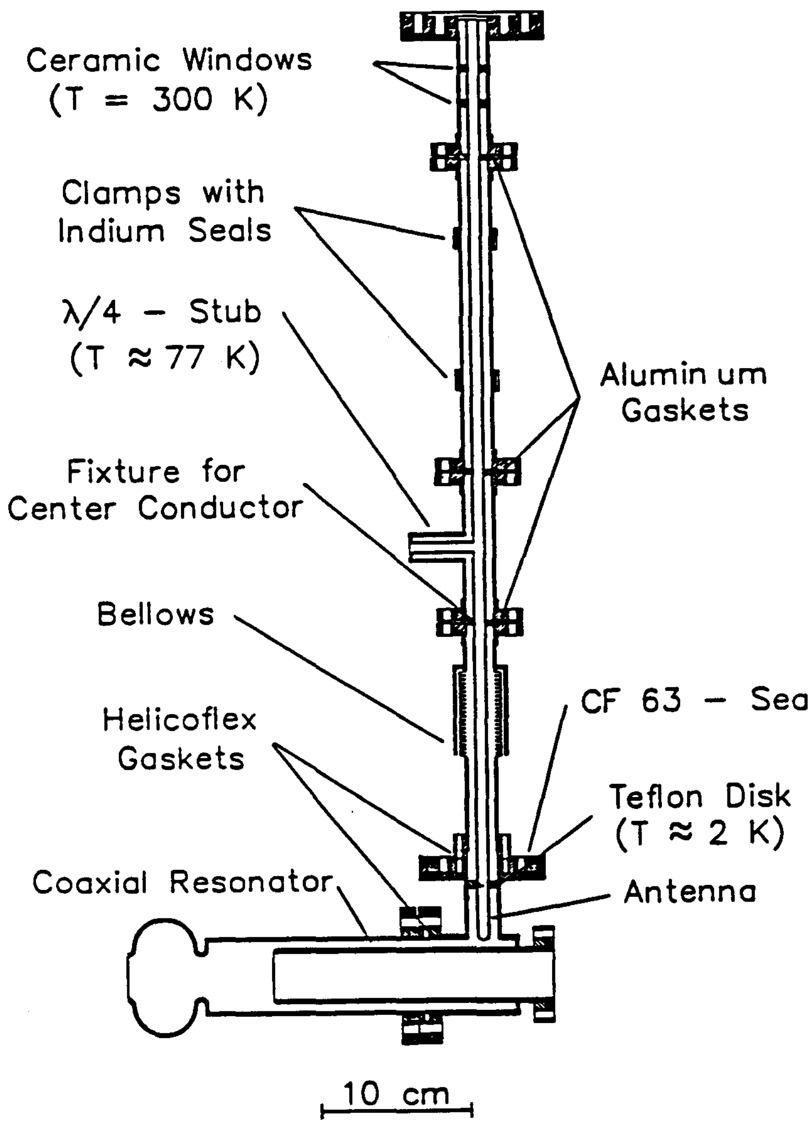

Fig. 3 *Variable input coupler with 7/8" coaxial RF input line*

While the coupling between the cavity and the intermediate resonator is fixed, the coupling between this resonator and the input line is determined by the distance between the center conductors of the line and the intermediate resonator. As a result, a variation of this distance by 16 mm changes the coupling from the RF input line to the superconducting cavity by almost four orders of magnitude as shown by the result of a measurement at 2 K, displayed in Fig. 4. This allows an optimization for operation with heavy beam loading (strong coupling) as well as for diagnostic measurements (weak coupling).

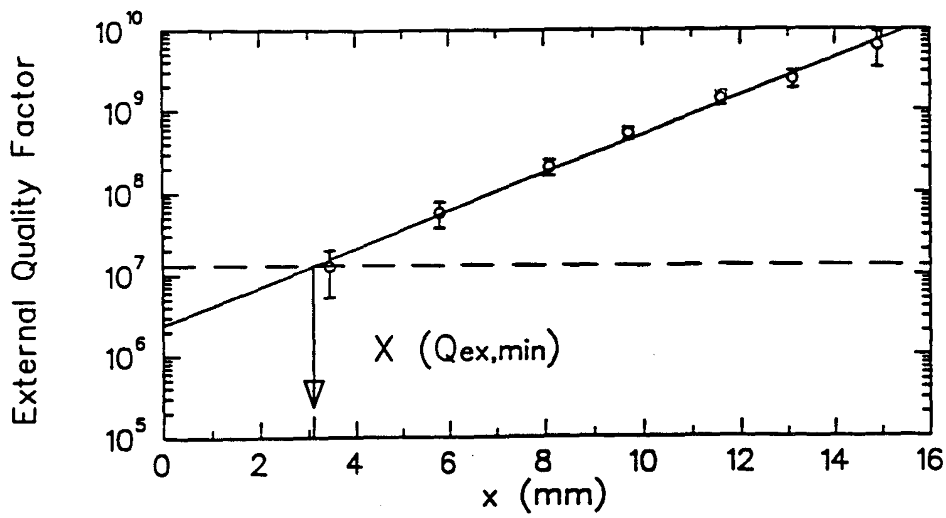

Fig. 4 *Performance of the variable input coupler at 2 K; x denotes the spacing between the center conductors of RF input line and intermediate coaxial resonator.*

The rigid mechanical construction of the intermediate resonator makes it insensitive to vibrations and its coaxial geometry guarantees the cylindrical symmetry of the electromagnetic field in the region passed by the electron beam. Because of the high current densities present in the intermediate resonator it had to be superconducting and is fabricated from niobium. Vacuum connections are accomplished by stainless steel flanges brazed onto the niobium tubes and two Helicoflex gaskets (cavity and RF input line) and an OFHC copper gasket (beam tube).

The design of the probe coupler is very similar to that of the input coupler. Again, an intermediate coaxial resonator performs the coupling between the cavity and the RF line. Since the overall coupling is weak (β = 0.25 corresponding to an external Q of $1.2 \cdot 10^{10}$), the probe coupler can be normalconducting and is manufactured from stainless steel. A prototype of the input coupler and several probe couplers have been installed in the accelerator since October 1992 and have been operated reliably for more than 2000 hours. In the meantime, couplers for all cavities of the S-DALINAC have been built and will be installed together with chemically retreated cavities (see Sect. VI).

V. Subharmonic Injection

In order to be able to drive the FEL installed at the S-DALINAC, the accelerator has to provide peak currents of 2.5 A. This could only be achieved by a reduction of the bunch repetition rate which has to be a subharmonic of the linac frequency. Therefore a pulsing option for the electron gun operating at a repetition rate of 10 MHz (300^{th} subharmonic) and a 600 MHz (5^{th} subharmonic) chopper / prebuncher system had to be incorporated into the 250 keV injection of the accelerator. The central part of Fig. 5 displays a schematic layout of the modified injection consisting of a 10 keV thermionic gun (1), a 250 kV electrostatic preaccelerator tube (2), a 3 GHz chopper / prebuncher system (3b, 5b) for nuclear physics operation, a 600 MHz chopper / prebuncher System (3a, 5a) for FEL operation, chopping aperture (4), and the (superconducting) 5-cell capture section (6). The upper and lower parts of Fig. 6 show the time structure of the electron beam at the locations indicated by the arrows for the two modes of operation.

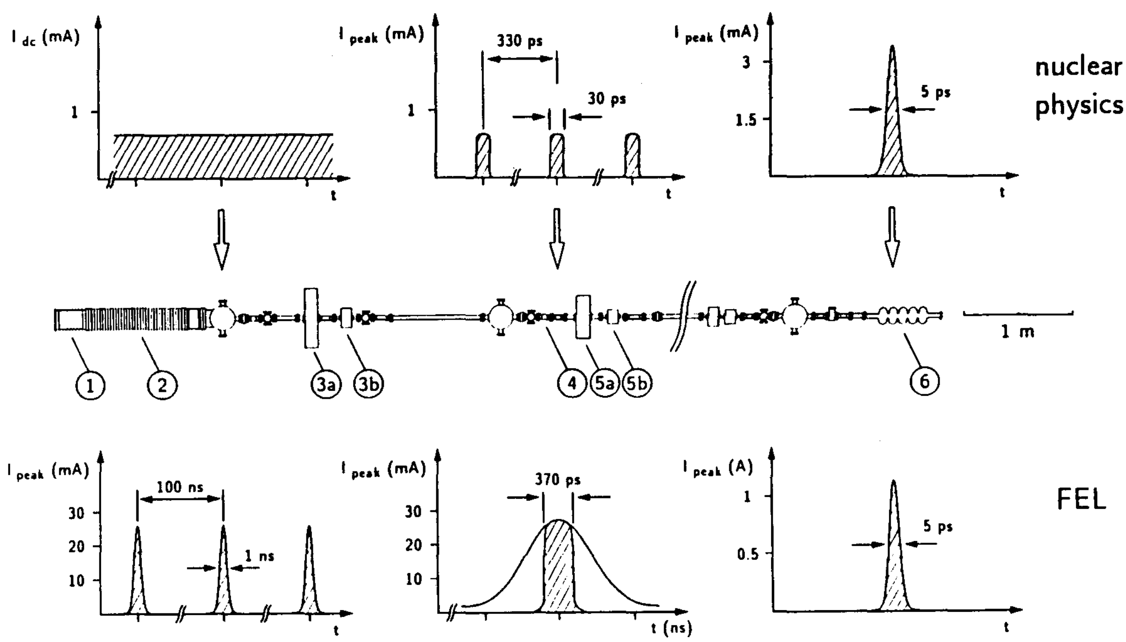

Fig. 5 *Time structure of the beam for 3 GHz cw (nuclear physics) and 10 MHz cw (FEL) mode of operation in the injection beamline. The figures denote: (1) electron gun, (2) 250 kV preacceleration, (3a) 600 MHz-, (3b) 3 GHz-chopper cavity, (4) chopper aperture, (5a) 600 MHz-, (5b) 3 GHz prebuncher cavity, and (6) 5-cell capture section.*

For nuclear physics experiments, a continuous wave time structure with electrons in each RF bucket is produced. The chopper cavity together with the watercooled chopper aperture chops the DC current from the electron gun into pulses with a length corresponding to 30° of the RF phase at the linac frequency. The prebuncher cavity compresses the width of these pulses to 6 degrees at the entrance of the capture section of the superconducting injector linac. Since all superconducting cavities have been designed for electrons with $\beta = 1$ and the 250 keV beam has a velocity correspondending to $\beta = 0.74$, the beam is both accelerated and bunched in the capture section and thus the bunch length is reduced to 2° at the end of the injector. For FEL operation the 1 ns wide pulses from the electron gun are chopped to a width of 370 ps by the 600 MHz subharmonic chopper and the chopper aperture. The subharmonic prebuncher then compresses the pulse width again to 6° (with respect to the 3 GHz linac frequency) at the entrance of the capture section. Similar to the 3 GHz continuous wave operation, the capture section together with the following two accelerating structures of the injector linac reduces the bunch length to 2° while increasing the peak current. Thus, the peak current corresponding to the emitted electron current of 27 mA from the gun amounts to 2.7 A.

VI. Outlook

The most important goal for the near future is of course to improve the Q_o of the cavities. We think that removing a few µm from the cavity surface by very clean, state - of - the - art chemistry, possibly including high pressure water rinsing, should raise the Q_o at least close to the design figure of $3 \cdot 10^{9}$. Therefore, in collaboration with DESY, two 20-cell cavities will undergo such a treatment, using the new facilities of the TESLA Test Facility at DESY. The two cavities will then be installed and tested in one of the cryomodules of the S-DALINAC. If the treatment proofs to be successful, a step by step improvement and replacement of the cavities could be performed, gradually raising the beam energy to its design figure of 130 MeV in cw operation. In case the chemical treatment should not be successful, the only remaining conclusion would be that firing the cavities at 750°C (see Sect. II) did not prevent the "hydrogen disease" completely, in which case a thermal treatment at higher temperatures would become necessary. In any case each replacement of cavities will be accompanied by the installation of new RF input- and probe couplers (see Sect. IV).

Two years of operaion of the S-DALINAC have shown that the optics of the recirculating beamlines react rather sensitive to small variations of the input beam parameters (orientation of the transverse phase space ellipses). In order to investigate and improve the situation, the first-order, interactive beam optics code XBEAM was developed. Its very fast graphics output on screen allowed to pinpoint those sections in the present optical system which are responsible for its unpleasantly sensitive behaviour. It turned out that one reason is the fact that the 16 m long main accelerator contains no focusing elements except the superconducting cavities themselves. Simulations showed that the installation of four small superconducting quadrupoles inside the linac cryostat and one normalconducting quad upstream will greatly improve the situation. In addition, a rearrangement of the quadrupoles in the straight sections of the recirculating beamlines, resulting in a more tolerant optical behaviour, is planned, accompanied by the development of new (probably low-Q) rf-cavities for on-line beam diagnostics.

Acknowledgement

We are much indebted to H. Lengeler for fruitful discussions and his continuous support. Stimulating discussions with E. Haebel, D. Proch, T. Weiland, and S. Wolff have been very helpful in the course of the project. The tremendous help of H. Gaiser and the galvanic workshop at GSI as well as the support from the mechanical workshop at CERN is gratefully acknowledged.

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